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EFFECT OF STRAIN RATE ON MECHANICAL PROPERTIES OF ALUMINUM-SILICON CARBIDE COMPOSITES

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Strain rate, or the rate at which a material is deformed, is an important consideration in the production, fabrication, testing, assessment and performance of materials. This rate can have a significant effect on mechanical properties of a material. The mechanical properties of heat treated cast aluminum-silicon carbide composite (A356+SiC_p) were investigated as a function of strain rate during conventional tension test in the range between 10^{-5} and 10^{-2} min^{-1}. The materials tested contained 0, 5, 10, 15 and 20 volume % of silicon carbide particulates with aspect ratio of 2:1 to 5:1. The results of tensile and fractographic investigation indicate very low strain rate sensitivity in the tested range for all materials.

1.0 INTRODUCTION

Discontinuously reinforced metal matrix composites based on aluminum alloy matrices hold a promise to overcome inherent material limitations of monolithic alloys and substantially enhance their useful engineering properties/1/. These materials can be used in applications where improvements in component performance and reliability can be achieved and are economically justified. For example/1/, by adding 20 volume % of SiC to a castable A356 aluminum alloy, the yield strength can be increased by 66% at room temperature and by 233% at 300°C. Smaller, but significant increases can be achieved in U.T.S., elastic modulus, etc. Combined with the improved tensile strength properties there is also a marked increase in the material resiliency. This is accompanied by some loss of ductility and fatigue life. These limitations may restrict the use of this type of material in some applications, unless further property improvements are made.

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The aluminum-particulate silicon carbide (Al-SiCp) composites are novel materials and a significant effort is underway to optimize and improve the properties that are adversely affected by the reinforcing material. Improvements are needed in tensile ductility and fatigue life, while maintaining superior strength and resiliency.

Castable aluminum-SiCp composites have achieved a dominant position in the metal matrix composites field because of their lower cost as compared with continuously reinforced materials and their isotropic, albeit more moderate mechanical properties. Furthermore, the fabrication routes for final products made of these materials are identical to those used for monolithic alloys, (i.e. permanent mold, sand and die casting processes). Composite castings, however, suffer from many of the same defects and deficiencies as conventional castings. Castings with excellent properties can be achieved by careful control of processing parameters, mold and tooling design.

In this work, the effect of strain rate in the range between 10^{-5} and 10^{-2} min^{-1}, was investigated on the mechanical properties of the castable A356 alloy reinforced with up to 20 volume % of SiC particulate. The purpose was to establish the sensitivity of these materials to this factor during conventional monotonic (pseudostatic) tension test. This information is necessary to facilitate design of safe and functional components for implementation into the electric power system.

2.0 EXPERIMENTAL PROCEDURES

2.1 Materials Used

The materials studied were composites of A356 aluminum matrix alloy and SiCp particles in the following amounts 0, 5, 10, 15 and 20 volume %. The A356 alloy and composites containing 15 and 20 volume % SiCp were cast from 100% virgin ingots (as received from manufacturer). The composite ingots were purchased from Duralcan USA, San Diego, California. The composites containing 5 and 10 volume % were prepared by melting together appropriate amounts of A356 alloy and the A356 + 20 volume % composite.

The nominal composition of A356 alloy is: 7.0% Si, 0.2% Cu max, 0.2% Ti max, 0.15% Fe max, 0.1% Mn max, 0.1% Zn max, 0.3% Mg and balance of aluminum.

The silicon carbide reinforcements were angular particles (median size 9.3 ± 1μm) with aspect ratio between 2:1 and 5:1.

2.2 Casting and Heat Treatments of Test Samples

The as received ingots of the starting materials were cut into ~1.0 kg pieces on a high speed carbide tipped band saw. Degreased and melted in a graphite crucible at 770 - 780°C in a resistance-heated box-type muffle furnace. The weight of a typical charge was ~1.0 kg. The melt holding time after complete melting was no longer than 30 minutes.

The melts containing SiCp were stirred, after removal from the furnace and before casting, for a period of 15-20 seconds using a 316 stainless steel rotary impeller driven by an electric hand drill.

The casting of 0.5 inch standard test bars (2 inches gauge length) as specified in ASTM-B577 was done in a cast iron (meehanite) mold with casting configuration specified in ASTM-B107-87. The mold was heated, before each casting, with a gas torch to 250-300°C.

Heat treatment of test specimens was carried out in a resistance-heated muffle furnace to T6 condition (solution heat-treated and then artificially treated) as specified in ASTM-B597. The heat treatment consisted of:

- Solutionizing at 540°C for 200 minutes
- Quenching in water at 60°C
- Aging at 171°C for 4 hours

All specimens were treated under identical conditions. The heat treatment process was monitored carefully by positioning several thermocouples in the heat treatment basket. The quench interval was less than 10 seconds.

2.3 Mechanical Testing

The heat treated samples were subjected to room temperature tensile tests in a hydraulically-driven universal tensile testing machine. The strain during testing was measured using a clip gauge (Baldwin Extensometer, Model No. PS 5M) with knife edges set for two inch gauge length. The machine was calibrated to yield strain rates of the test specimen gauge length between 10^{-5} and 10^{-2} min^{-1}. The yield strength (0.2% proof strength), ultimate tensile strength (UTS) and elongation were determined from the load vs. elongation data.

2.4 Microstructural Examination

The as-cast and heat treated test specimens were examined by optical microscopy to identify the microstructural components of the materials and assess the changes occurring during the heat treatment. The metallographic samples were obtained by sectioning the gauge portion of the test specimens.

The fracture surfaces of tensile specimens were examined under optical and scanning electron microscopes.

3.0 RESULTS

3.1 Microstructure

The microstructures of the cast and heat treated test samples before tensile testing are shown in Figures 1 to 5. The Figure 1 depicts a typical cast structure of A356 resulting from dendritic solidification with the characteristic segregation of eutectic phase between the dendrites. Close observation indicates that the eutectic Si was spherodized during the heat treatment cycle and exhibits an optimum morphology (small spherical particles).

Figures 2 to 5 illustrate the location and distribution of the SiCp reinforcement particles. The particles are invariably located in and incorporated into the eutectic interdendritic phase. The distribution of SiCp is uniform in samples prepared from virgin ingots containing 15 and 20 volume % SiCp (Figures 4 and 5). The samples, prepared by melting together A365 and A365 + 20 volume % SiCp material, exhibit SiCp particle clustering (Figures 2 and 3). The matrix alloy in the composites has the same morphology as the A356 shown in Figure 1.

3.2 Effect of Strain Rate on Mechanical Properties

The measured mechanical properties of heat treated (T6) samples investigated, the average values of yield strength (YS), ultimate tensile strength (UTS), and percent (%) of elongation are plotted in Figures 6, 7 and 8 as a function of strain rate during tensile testing. These results indicate that there is no significant effect of the strain rate on yield and ultimate tensile strengths within the investigated range. The elongation of the composite materials was affected to only a very small degree. The heat treated A356 material exhibited significant increase in the elongation at the lowest tested strain rate; from 1.8% at 10^{-2} min^{-1} to 2.8% at 10^{-5} min^{-1}.

The results of tests performed in this study were within the range of values reported by Duralcan USA Inc./1/. However, the observed strengthening effect of SiCp additions on the YS and UTS of the A356-T6 alloys in this work was lower. The reason for this discrepancy could not be established since it was not possible to determine the exact nature of the Duralcan USA Inc. tests from the available information.

3.3 Morphology of Fracture Surfaces

Fracture surfaces were examined by scanning electron microscopy following tensile testing.

Figure 9 shows fractographs of cast and heat treated A356-T6 alloy tensile tested at two strain rates: 10^{-2} and 10^{-5} min^{-1}. The fracture surfaces are fibrous in appearance and consist of coalesced voids, which is characteristic of ductile fracture. The voids are nucleated on Si particles. This leads to the formation of a cellular structure. Cracked or debonded eutectic silicon particles were observed in the middle of almost all larger cells. The small cells do not contain these particles. These observations are in agreement with previous studies/2/ postulating that the fracture of this material occurs in three stages:

i) Crack initiation at the eutectic Si particles.

ii) Propagation of cracks in the interdendritic region.

iii) Rupture of matrix.

Visual inspection and comparison of the two fractographs in Figure 9 reveals, that the characteristic features of both fractures are virtually identical, in both size and extent. This confirms the results of the tensile tests (see Figure 7), indicating that the strain rate in the investigated range has no effect on the mechanism or kinetics of the fracture process.

The fracture surfaces of A356-T6 + 20 volume % SiCp after tensile testing, shown in Figure 10, are again indicative of ductile fracture in the matrix, accompanied by fracture of the SiC reinforcement particles many of which are fractured. The fracture surfaces have a cellular structure; large cells around SiC particles, smaller cells with eutectic Si particles in the middle and small cells indicating plastic decohesion/rupture of the matrix material. These observations confirm previous findings/3/, suggesting that the voids and thus fracture originate at the SiC particle/matrix interface.

The virtually identical topology of the fracture surfaces over a change in strain rate of two orders of magnitude shown in Figure 10, confirms again the results of the tensile tests (see Figure 7). The strain rate in the investigated range has no effect on the mechanism and kinetics of the fracture process.

Polished cross sections through the fracture surface of A356-T6 + 20 volume % SiCp material tested at two extreme strain rates are shown in Figure 11. Close examination of these micrographs did not reveal the SiC particle fracturing and void formation at the metal/SiC interface which was deduced from the fracture surface investigation.

4.0 DISCUSSION

Strain rate, or the rate at which a material is tested by deformation may have an effect on the properties, which are important for the design of safe and functional power system components. All three fundamental design properties (YS, UTS, % elongation) can be potentially affected. This information is needed to design and fabricate reliable components which do not endanger public safety and/or result in economic loss.

During a conventional tension type test, ASTM B577M prescribes an upper limit of about 10^{-2} min^{-1} (1.66×10^{-4} s^{-1}) for determining a yield strength of wrought and cast aluminum alloy products. This limit is based on a consensus reached between voluntary participants during the standard development and data published in literature/4/. The results of reported tests indicate, in general, that below 10^{-3} s^{-1} the mechanical properties of aluminum and aluminum alloys are not sensitive to strain rate. Similar information is not available on the sensitivity of Al-SiCp

composites. Therefore, the purpose of this work was to investigate the behaviour and properties of A356-T6 + SiCp composites in the conventional tensile testing range; 10^{-5} to 10^{-2} min^{-1}.

Only minimal effect on the material properties was anticipated in the elastic deformation regime, since there is virtually no material flow involved at the investigated strain rates. The results of the present tests (see Figure 6) confirmed this assumption. The yield strength of the tested materials remained practically constant.

In the plastic deformation regime, an effect was possible due to restriction of the matrix material flow by the reinforcing SiC particles. Higher elongation and lower UTS were anticipated at lower strain rates. Close inspection of the Figure 8 indicates that there is a slight increase in the % elongation at the low end of the tested range. The UTS appears to be not affected (Figure 7).

The lack of A356-T6 + SiCp composite response to changing strain rate suggests that the mechanism of material deformation and fracture does not change in the tested range. As a consequence, the properties of these materials can be reliably determined when tested under these conditions.

5.0 CONCLUSIONS

The following main conclusions can be drawn from this work:

i) The mechanical properties (yield strength and ultimate tensile strength) are not affected by strain rate in the range between 10^{-5} min^{-1} and 10^{-2} min^{-1}.

ii) The elongation during the tensile testing in the same range of strain rates showed slight increase at the lower rates.

iii) The detailed fractographic investigation revealed that the fracture of the composite materials occurs in three stages:

- crack initiation at the SiCp/matrix alloy interface and at eutectic Si particles.
- propagation of the cracks in the interdendritic region
- rupture of the matrix alloy

iv) The fracture surface morphology indicates that the fracture process does not change with the strain rate. This is consistent with the observed insensitivity of the mechanical properties to changing strain rate.

6.0 RECOMMENDATION

The mechanical properties of A356-T6 + SiCp composites, determined in the strain rate range between 10^{-5} and 10^{-2} min^{-1}, can be used for design, analysis and specification of components made of this material where appropriate.

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7.0 REFERENCES

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FIGURE 1

POLISHED CROSS-SECTION OF CAST A356-T6 BEFORE TENSILE TESTING

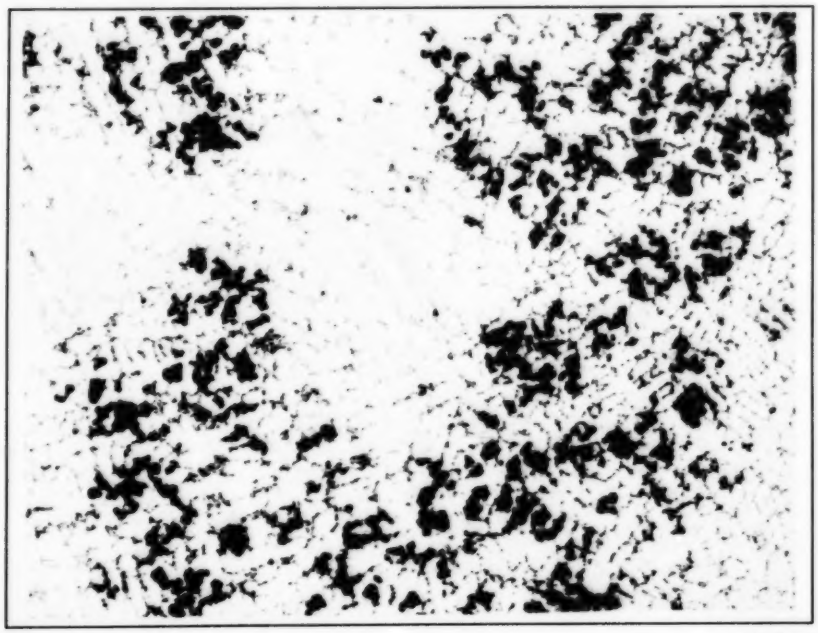
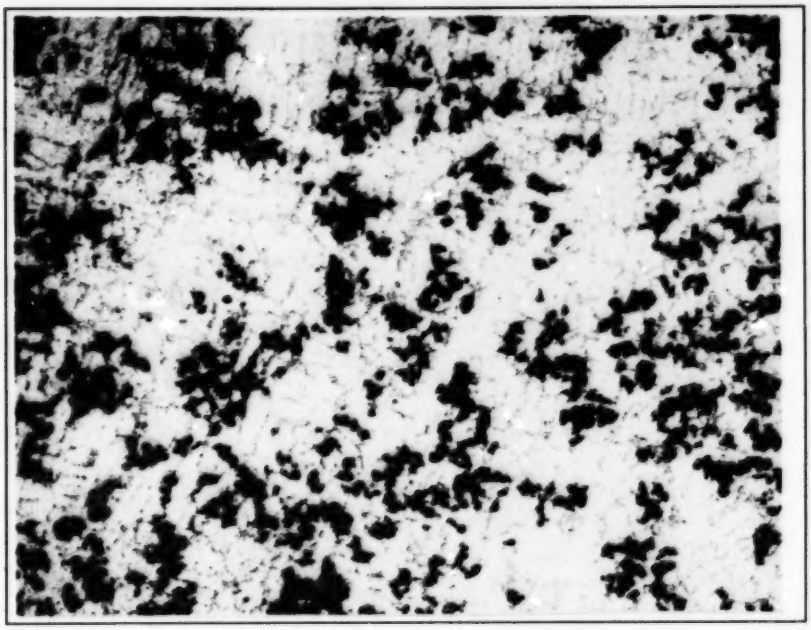


FIGURE 2

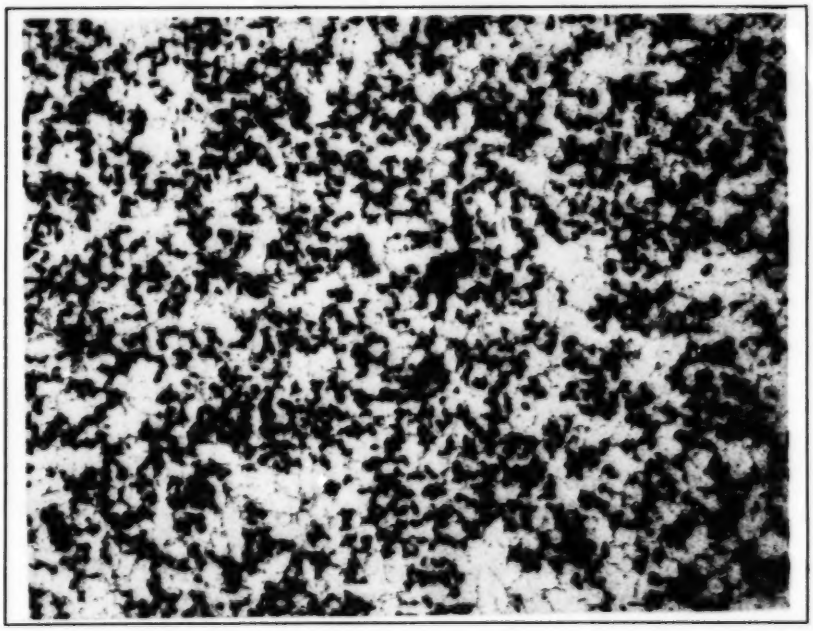
POLISHED CROSS-SECTION OF CAST A356-T6 + 5 VOL % SiC_p BEFORE TENSILE TESTING



100 µm

FIGURE 3

POLISHED CROSS-SECTION OF CAST
A356-T6 + 10 VOL % SiC_p BEFORE TENSILE TESTING



100 µm

FIGURE 4

POLISHED CROSS-SECTION OF CAST
A356-T6 + 15 VOL SiC_p BEFORE TENSILE TESTING

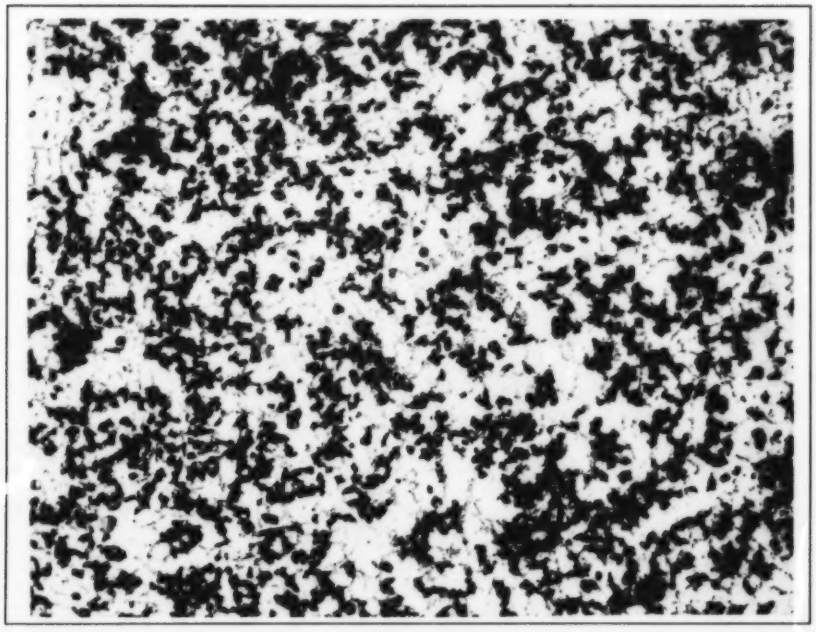
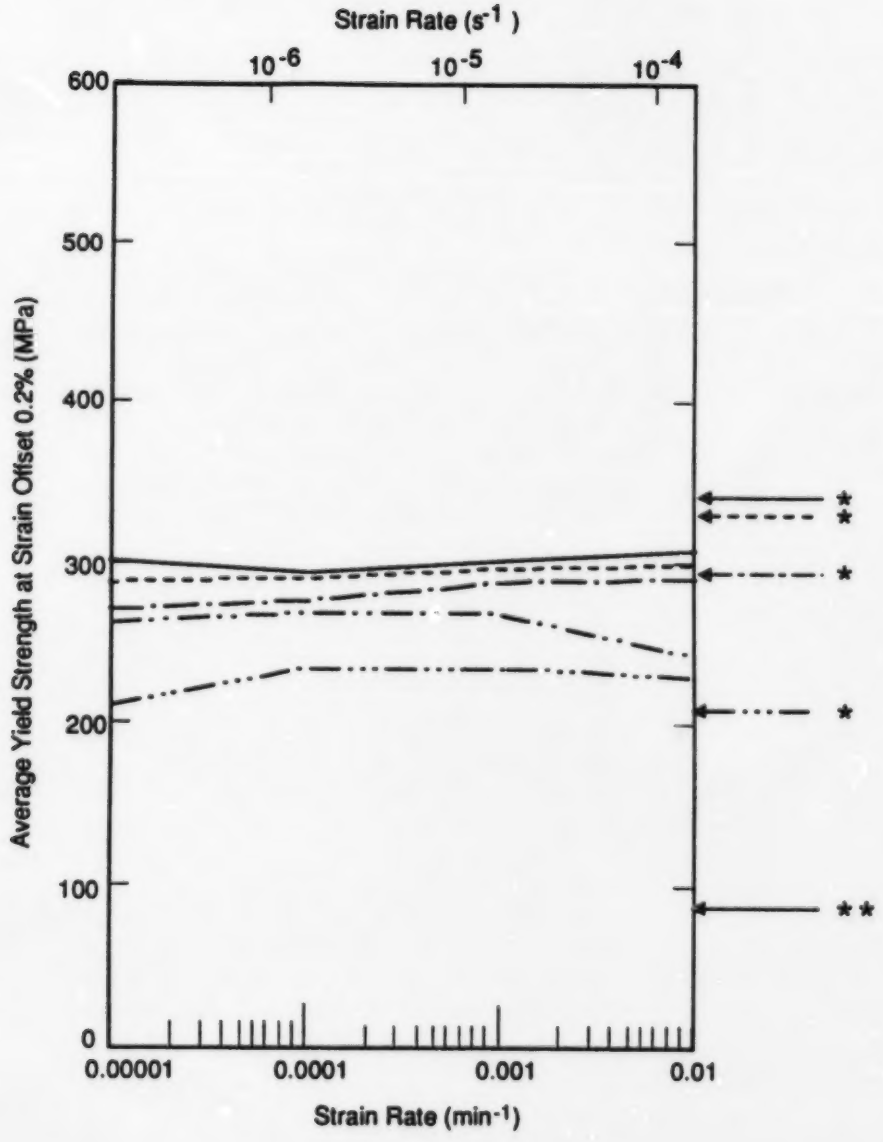


FIGURE 5

POLISHED CROSS-SECTION OF CAST A356-T6 + 20 VOL % SiC_p BEFORE TENSILE TESTING



This Work:

- A356 - T6
- + 5 Vol % SiC_p
- + 10 Vol % SiC_p
- + 15 Vol % SiC_p
- + 20 Vol % SiC_p

* Values Reported by Duralcan USA (Ref 1.)

** Ontario Hydro Line Procurement Specification LPS-X4S-51052-2002-85a (Ref 5.)

FIGURE 6

DEPENDENCE OF YIELD STRENGTH OF A356 + SiC_p (HEAT TREATED TO T6 CONDITION) ON STRAIN RATE DURING TENSILE TESTING

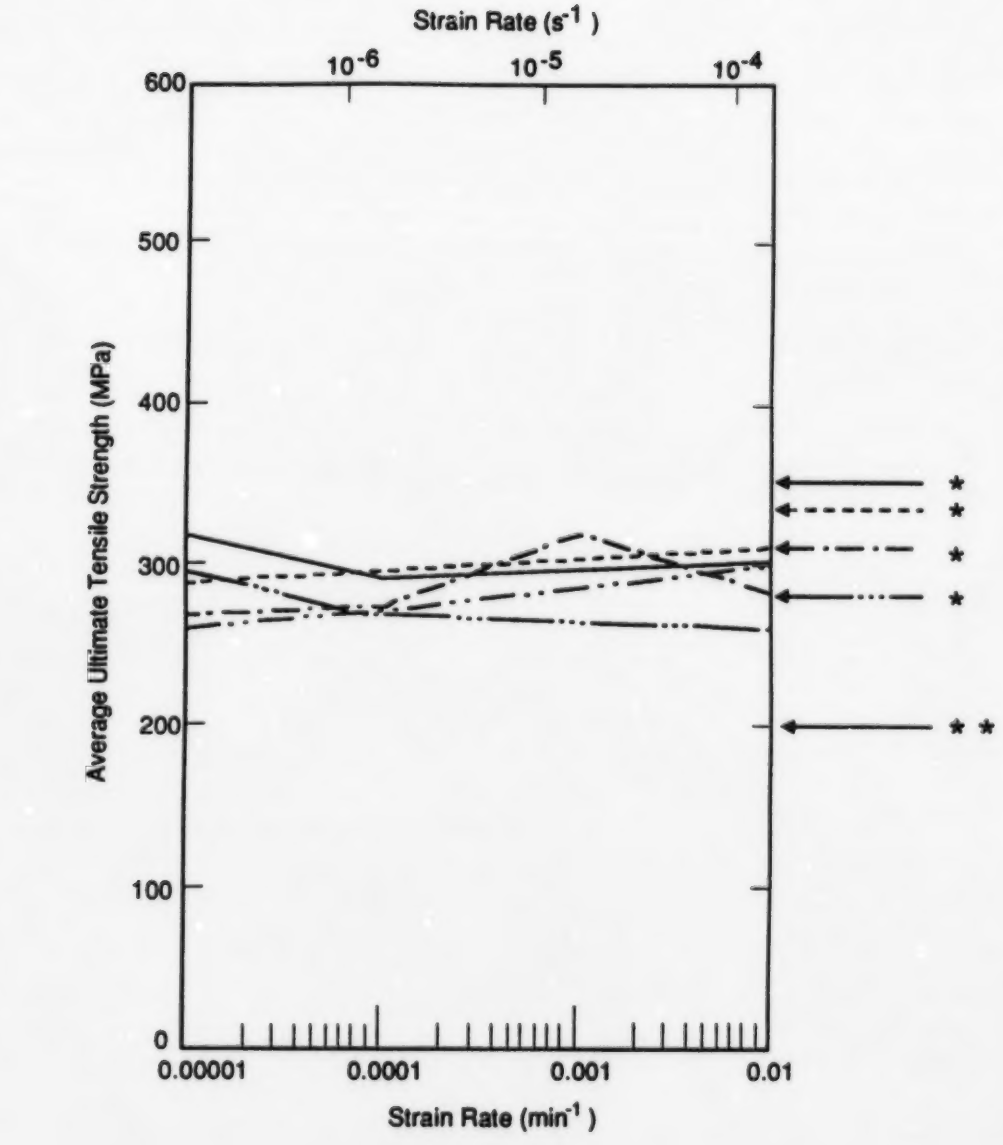
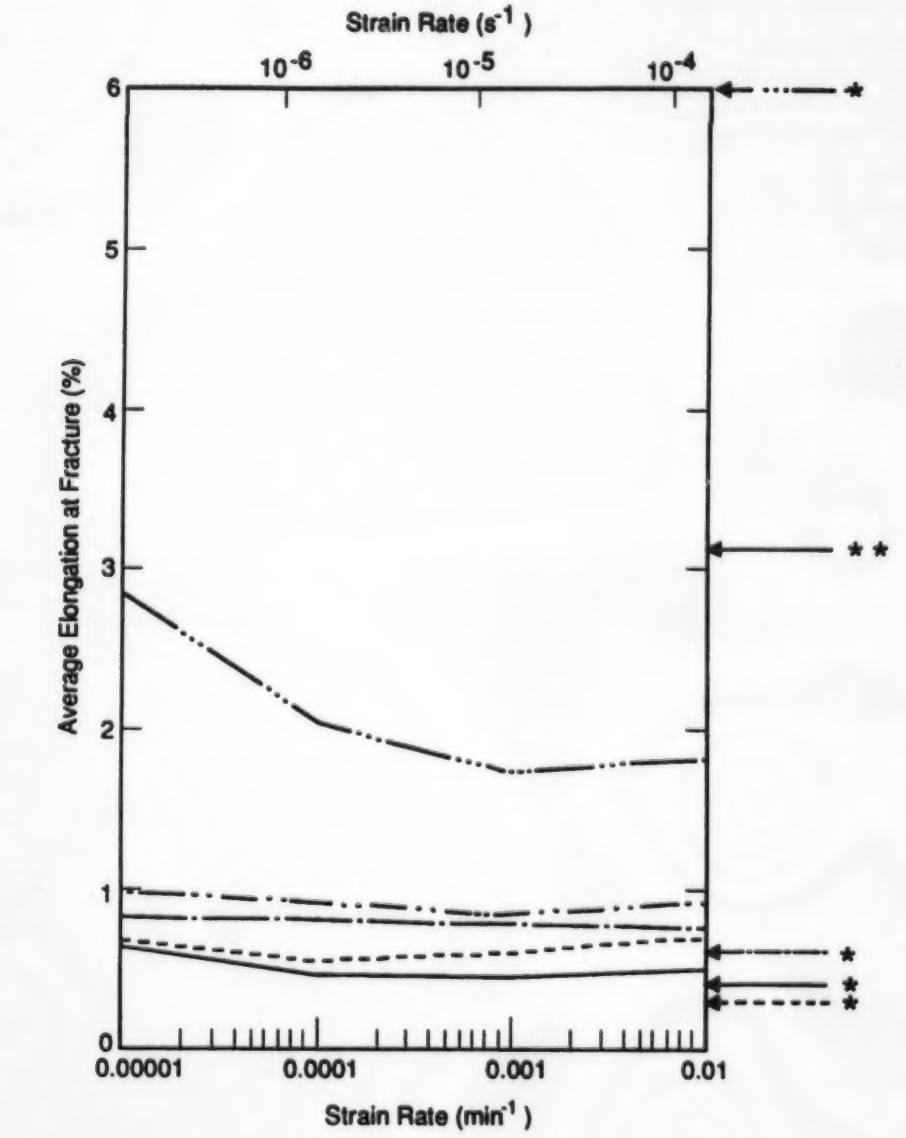


FIGURE 7

DEPENDENCE OF ULTIMATE TENSILE STRENGTH OF A356 + SiC_P (HEAT TREATED TO T6 CONDITION) ON STRAIN RATE DURING TENSILE TESTING



This Work:
- A356 - T6
- + 5 Vol % SiC_p
- + 10 Vol % SiC_p
- + 15 Vol % SiC_p
- + 20 Vol % SiC_p

* Values Reported by Duralcan USA (Ref 1.)

* * Ontario Hydro Line Procurement Specification LPS-X4S-51052-2002-85a(Ref 5.)

FIGURE 8

DEPENDENCE OF ELONGATION OF A356 + SiC_p (HEAT TREATED TO T6 CONDITION) ON STRAIN RATE DURING TENSILE TESTING

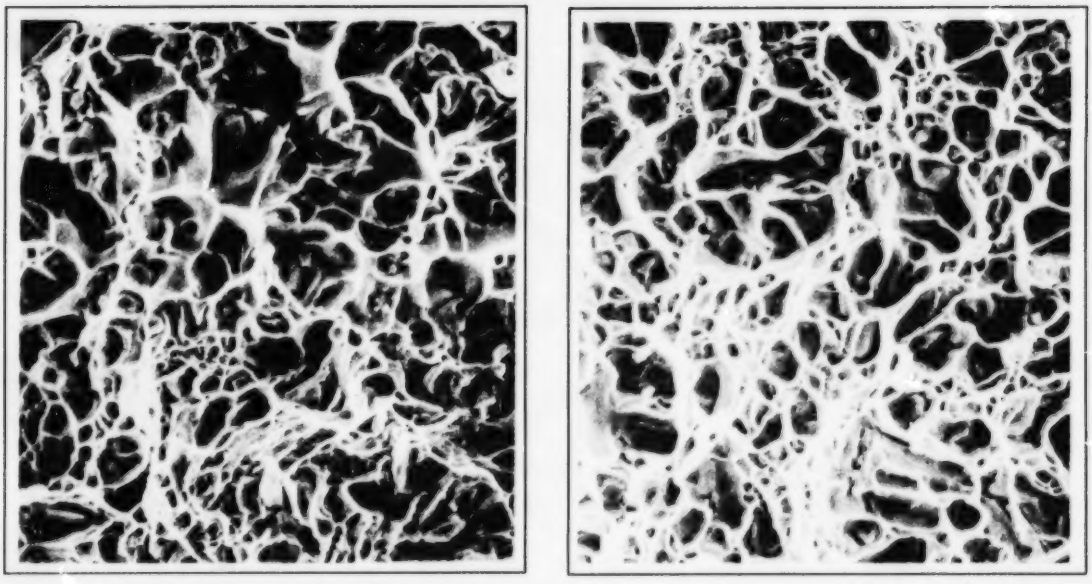


FIGURE 9

FRACTURE SURFACES OF CAST A356-T6 ALLOY AFTER TENSILE TESTING

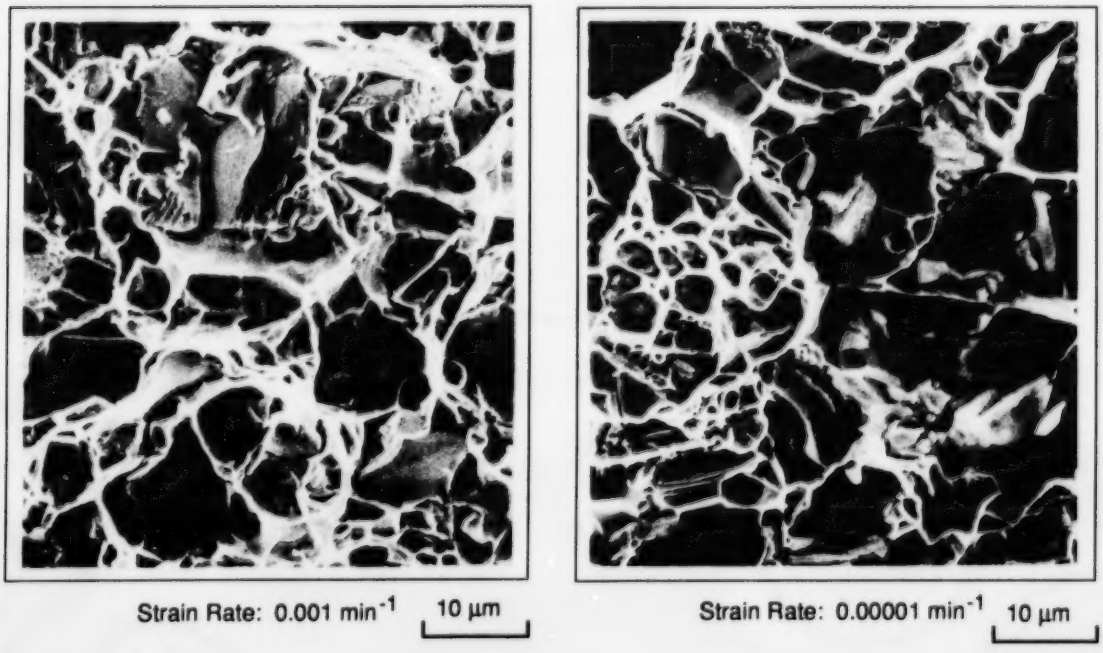


FIGURE 10

FRACTURE SURFACES OF CAST A356-T6 + 20 VOL % SiC_p AFTER TENSILE TESTING

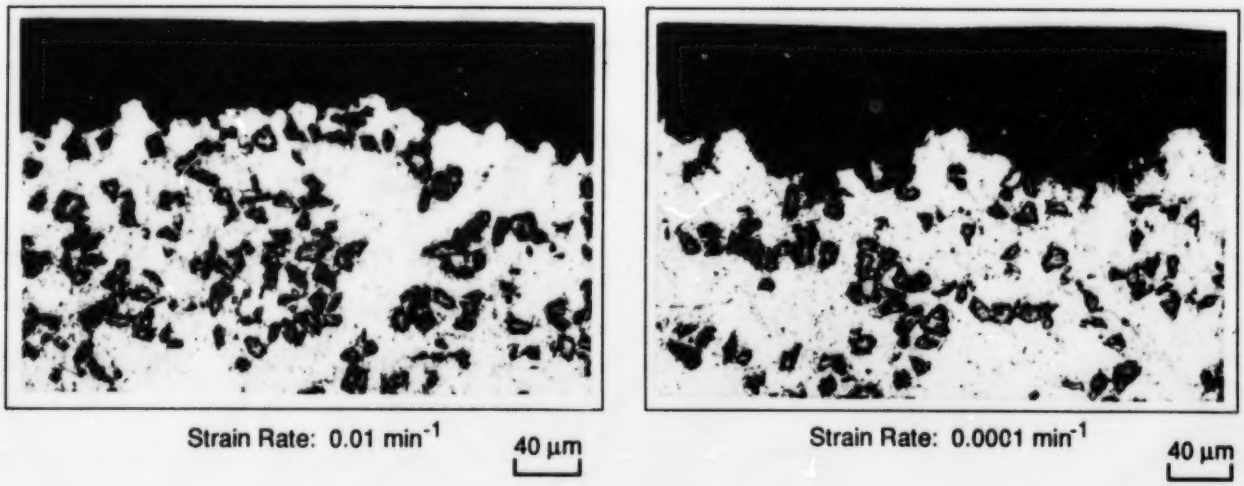


FIGURE 11

A POLISHED CROSS-SECTIONS BELOW THE FRACTURE SURFACES OF CAST A356-T6 + 20 VOL % SiC_p AFTER TENSILE TESTING